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G-LAS: a ring laser gyroscope for high accuracy angle measurements

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Abstract. Angle measurements at the uncertainty level of tens of nanoradian are needed in many applications, from precision mechanical industry to astronomy, geodesy and experimental physics. Nowadays state of the art instruments to measure large angles, i.e. angular encoders, can achieve resolutions to the nanoradian level, but the traceability to the angle unit is not guaranteed at the same level of uncertainty. A novel ring laser gyroscope has been designed and built in a joint research project between INRIM and INFN. The device is based on a gyroscope 50 cm in side-length mounted on a precision rotating table. Exploiting the Sagnac effect, it will behave as an ideal angular encoder capable of generating and measuring angles over the full circle interval with a target accuracy of the order of 10 nrad.

1. Introduction

High accuracy angle measurements are required in many applications ranging from precision engineering to astronomical telescope or experimental physics. Nowadays resolutions at the nanoradian level can be achieved by commercial instruments such as autocollimators (ACs) and angular encoders (AEs). The latter are based on the division of the circle in equal parts and are generally used to implement angle standards, since they can generate and measure also large angles. Unfortunately, the accuracy of AEs is limited by two main effects: an uneven division of the circle in equal parts (due to grating lines manufacturing errors or to a non-perfect centering of the encoder in the rotating structure) and the interpolation errors, mainly due to the optical reading system that subdivide the interval between two grating lines. In the best case, these errors can amount to few microradian for high end encoders, therefore in case of applications where high accuracy are needed, any angular encoder has to be calibrated with respect to a better quality angle standard, such as the state of the art angle standards maintained in the National Metrological Institutes (NMIs) [1-4]. An alternative approach to AE is a goniometer based on a ring laser gyroscope (RLG). Two laser beams counter-propagate in a ring cavity: when the RLG is rotated, the two beams experience a differential length of the effective optical path. This produces a relative frequency shift (Sagnac frequency) between the two oppositely travelling beams, which is proportional to the angular speed, according to equation (1)



$$f_{\text{sagnac}} = \frac{4A}{\lambda p} \vec{\Omega} \cdot \hat{n} = K \Omega \cos \theta \quad (1)$$

where A is the area and p is the perimeter of the ring cavity, λ is the laser wavelength, Ω is the angular speed and θ is the angle between the rotation axis and the area vector \hat{n} . The factor $K=4A/\lambda p$ is the RL gyroscope sensitivity.

A RLG can be seen as a very high resolution angular encoder, since the interference fringes by the two counter-propagating beams divide the full 2π angle into a number $N_{2\pi}=p/\lambda$ intervals.

$$N_{2\pi} = \frac{1}{2\pi} \int_{t_0}^{t_0+T} f(t) dt = \frac{K}{2\pi} \int_{t_0}^{t_0+T} \Omega(t) dt = K \quad (2)$$

Hence the value of a rotation angle Φ can be inferred by the equation $\Phi=2\pi N_{\Phi}/N_{2\pi}$, being N_{Φ} the number of fringes counted by beating the two counter-rotating beams when the table rotates by Φ .

$$N_{\Phi} = \frac{1}{2\pi} \int_{t_0}^{t_0+\Phi} f(t) dt = \frac{K}{2\pi} \int_{t_0}^{t_0+\Phi} \Omega(t) dt = K \frac{\Phi}{2\pi} \quad (3)$$

In case the RLG is placed on a continuously rotating table with a constant angular speed, the K factor of the RLG can be accurately determined, without a priori knowledge of the geometry of the instrument, thus allowing a self-calibration of the RLG. This property has been exploited by small dimensions RLG, as for example the apparatus developed by Yu. V. Filatov and collaborators [5].

In this paper we will describe the RLG for high accuracy angle measurement (GyroLaser Angular Standard, G-LAS) that has been designed and built in a joint research project between the Italian National Institute for Metrologic Research (INRIM) and the Italian Institute for Nuclear Physics (INFN), with a target angular accuracy of the order of 10 nrad.

2. The INRIM-INFN ring laser gyroscope, G-LAS

G-LAS is based on a square optical cavity delimited by two concave ($R=4\text{m}$) and two flat high quality mirrors (reflectivity larger than 99.99% and surface roughness better than 0.1 nm) fixed to high-quality mounting with piezoelectric drives. The cavity is 50 cm in side-length and is contained inside a vacuum chamber (see fig. 1) made by four angular towers connected together by means of steel pipes.

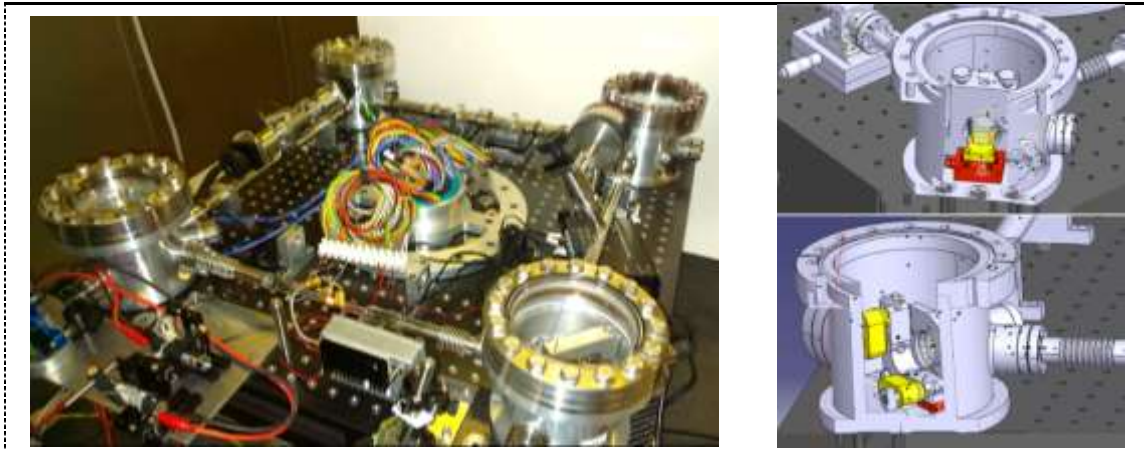


Figure 1. Left: picture of the G-LAS mounted on the carbon fibre board. Right: sketch of the vacuum chambers with details of the mirror mounts and the combinator prism.

The vacuum chamber is mounted on a $70 \times 70 \text{ cm}^2$ board realized by a carbon fibre honeycomb, closed between two layers of carbon fibre panels. The choice of carbon fibre was driven by its properties of stiffness and lightness and for its moderate thermal expansion coefficient. The chamber is filled with He-Ne gas mixture. A getter pump, which is active for molecular gases and not for noble gases, keeps the purity of the mixture in time. The active medium is excited by external electrodes through a radiofrequency discharge on a glass capillary sealed in the middle of one side.

The beams exit the vacuum chamber through two vacuum windows placed in the towers adjacent to the discharge and are combined together on a photodiode, connected to a data acquisition device.

The board is mounted on a high-precision air-bearing rotary stage manufactured by Aerotech, model ABRS-300MP, with an integrated direct driving motor and a high accuracy optical encoder. By the high accuracy manufacturing it claims a sub-microradian rotation errors and a resolution in angle position better than $0.2 \mu\text{rad}$. Moreover, a sophisticated control system should provide a constant speed rotating rate Ω , with a relative error $\Delta\Omega/\Omega$ lower than 10^{-5} . Further details can be found in [6-7]. The device has been operated in 2017 and preliminary results are reported in [8].

3. Comparison with other angle standards

In order to validate G-LAS as an angular standard, several different comparisons with other angle standards are foreseen.

- Comparison between G-LAS and Aerotech turntable.

The first step will be devoted to accurately measure the sensitivity constant K . To reach the goal of an angular uncertainty of 10 nrad , K must be known at the level of 10^{-9} . To this aim, signals coming from the ring laser will be compared with the ones coming from the optical encoder embedded into the Aerotech turntable, as shown in the upper part of fig. 2. The effect of different rotating speed will be investigated.

- Comparison between G-LAS and angle reference standard by means of a transfer standard.

In the second test, G-LAS will be used to calibrate an artefact previously calibrated with the INRIM angle standard. The angle reference standard, called REAC (rotating encoder angle comparator), is based on a double air bearing structure where a continuously rotating encoder is embedded and is able to reach an uncertainty level of the order of 100 nrad [4]. The artefact is a 12-sided polygon made of steel manufactured by Möller Wedel Optical. The polygon will be centred on top of the G-LAS and an autocollimator (AC) will aim at the polygon faces in order to detect the time t_j when the j -face of the polygon is in front of it, as shown in lower part of fig. 2. The angles of the polygon will be measured by counting the interference fringes between t_{j+1} and t_j and applying equation (3).

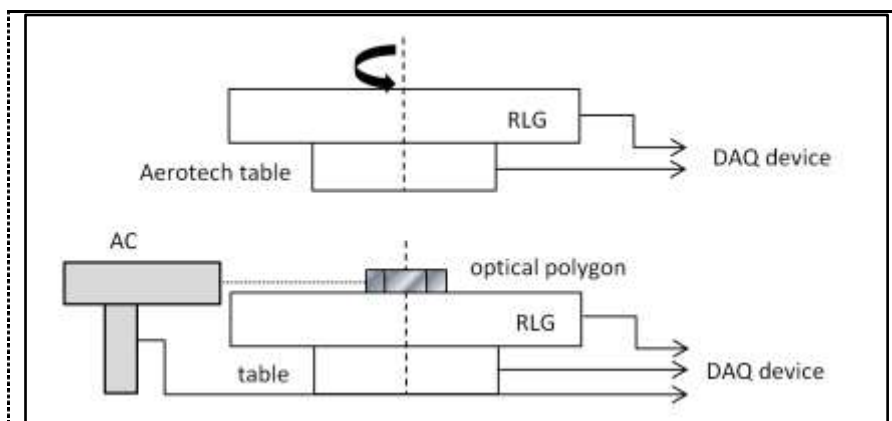


Figure 2. sketch of the comparison set-up: above, set-up for the comparison between the RLG and the rotating table; below, set-up for the comparison between the RLG and the angle standard

- Direct comparison between Aerotech turntable and the angle reference standard.

In the end, the Aerotech turntable will be placed on top of the REAC so that the rotation axis of the table is coaxial with the REAC axis within few tens of micrometres (see fig. 3). A structure will fix and support the outer part of the table, while a shaft will rigidly connect the rotating table with the angle standard, so that the motor will drive simultaneously the Aerotech table and the

angle standard. In this configuration, it will be possible to measure the table rotation errors and test to what extent the rotation speed is constant.

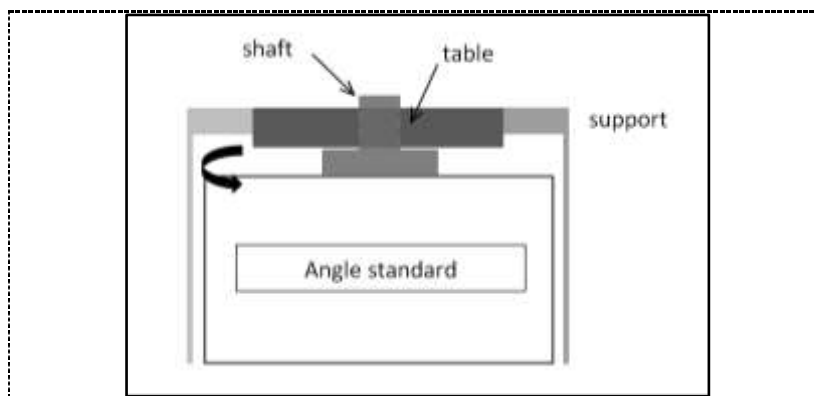


Figure 3. sketch of set-up for the comparison between the rotating table and the angle standard

4. Conclusions

A ring laser goniometer (RLG) called G-LAS has been realized at INRIM in collaboration with INFN Pisa. The G-LAS is the largest portable RLG capable of spinning on its axis. This unique feature allows self calibration of the device which is not possible on large fixed RLG's. The G-LAS will be calibrated and validated against the INRIM's primary angle standard. The use of G-LAS as a ultra sensitive gyroscope and angular standard is foreseen.

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